Chapter 16

Magnetic Fields & Electromagnetism

Slovak designer Matúš Procháczka came up with this concept for a car powered by magnets. The MAG would require all roads to be made out of giant magnets, which is something that would be very expensive and logistically difficult to implement. If the road did have the magnets then the magnetic force between the road and the magnets in the car would push the car up from the road and reduce the effective weight of the car by 50%. The car also has a polarized electric battery powered engine.The concept car won the unseen technology award at the Interior motives design award for 2007.

Syllabus 9646

16. Electromagnetism

Content
• Force on a current-carrying conductor
• Force on a moving charge
• Magnetic fields due to currents
• Force between current-carrying conductors

Learning Outcomes

Candidates should be able to:

(a) show an appreciation that a force might act on a current-carrying conductor placed in a magnetic field.

(b) recall and solve problems using the equation $F = B\ I\ l\sin\theta$, with directions as interpreted by Fleming's left-hand rule.

(c) define magnetic flux density and the tesla.

(d) show an understanding of how the force on a current-carrying conductor can be used to measure the flux density of a magnetic field using a current balance.

(e) predict the direction of the force on a charge moving in a magnetic field.

(f) recall and solve problems using $F = B\ Q\ v\sin\theta$.

(g) describe and analyse deflections of beams of charged particles by uniform electric and uniform magnetic fields.

(h) explain how electric and magnetic fields can be used in velocity selection for charged particles.

(i) sketch flux patterns due to a long straight wire, a flat circular coil and a long solenoid.

(j) show an understanding that the field due to a solenoid may be influenced by the presence of ferrous core.

(k) explain the forces between current-carrying conductors and predict the direction of the forces.

16.1 Introduction

More than 2000 years ago, the Chinese discovered the magnetic phenomena and have since been using it for navigation. However, it was only in the 1700s that magnetic properties and phenomena were studied in greater depth. Major discoveries made in the last 300 years have made a significant impact on our lives today. Scientists who have contributed significantly to our understanding of the magnetic phenomena include Ampere, Oersted, Gauss, Henry and Faraday.

Magnetism has many useful applications in our everyday lives. Earth's magnetic field not only allow us to find our way around but also enable birds to navigate when they migrate South during winter in the North. Nuclear Magnetic Resonance (NMR) which makes use of atoms' magnetic moments allows us to capture images inside our body. Handphones, speakers and microphones make use of concept of electromagnetic induction. The Great Industrial Revolution would not have been possible without the knowledge that the cutting of magnetic flux can generate electricity.

In the lectures on Electric Field, we have studied forces due to charges. You have learnt that there are two types of charges: positive and negative. In this topic, you will learn about forces due to magnetic fields, how magnetic fields can be generated and subsequently how electricity can be generated using magnetic fields. We will again be dealing with charges as moving charges generate a magnetic field.

16.2 Review of GCE O level Content

The core concepts of electromagnetism that is to be learnt at 'A' level is actually the same as at 'O' level. The main advancement to 'A' level electromagnetism is a more quantitative based approach with more applications. We will thus do a quick review of what was taught at 'O' level before proceeding to explore more of the wonders of electromagnetism.

1. Like poles repel, Unlike poles attract.

2. Whenever there is a current, there will always be a magnetic field associated with it.

You have learnt that the Right Hand Grip Rule allows you to determine the direction of the magnetic field due to a current.

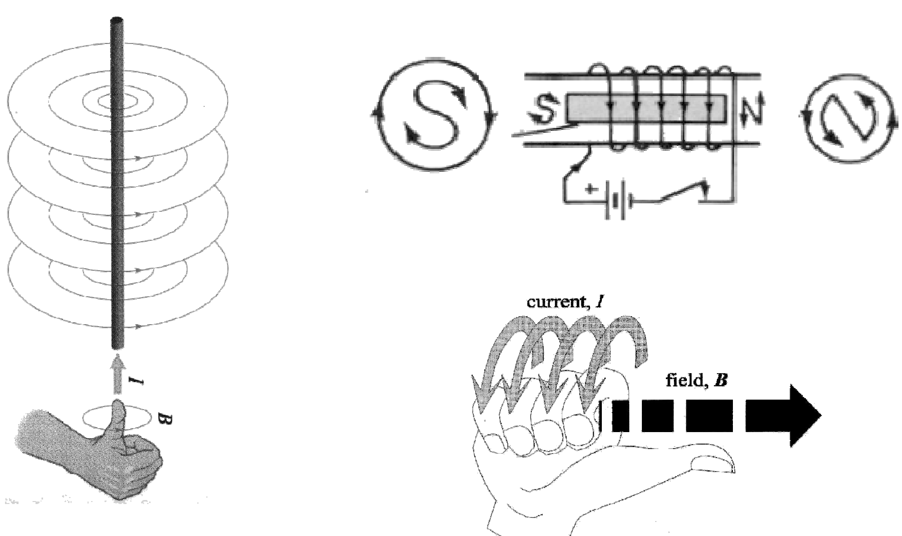


Figure 16.2.1 Using the right hand grip rule to determine the direction of the magnetic field due to a current

3. Current in a Magnetic field experiences a ***deflecting Force****.*

You have learnt that Fleming's Left Hand Rule allows you to determine the direction of the force deflecting a current-carrying conductor in the vicinity of a magnetic field.

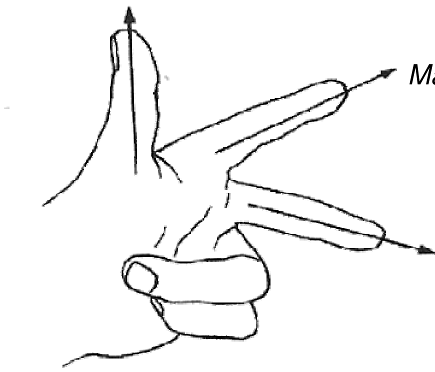


Figure 16.2.2 Fleming's Left Hand Rule

4. List of symbols

Unlike the topics that you have handled until now, electromagnetism is a topic based in 3 dimensional space. The topic requires quite a bit of spatial imagination.

The following are the main symbols used in diagrams:

$\otimes$ Into the page

$\odot$ Out of the page

B – Magnetic field / Magnetic field strength / Magnetic flux density

I – Current

F – Force

16.3 Magnetic Fields

16.3.1 The Magnetic Field and Magnetic Flux Density

Like gravitational and electric fields, magnetic field is an example of a '*field of force*'. The concept of a field illustrates '*action at a distance*' which means that a suitable object placed in the field can experience a force even though there is no physical contact with the object generating the field.

A magnetic field is the region of space around a magnetic substance where a moving charge/current carrying conductor will experience a magnetic force due to the magnetic substance.

Historically, the symbol ***B*** has been used to represent a magnetic field. Magnetic field is a **vector quantity** and its *direction at any location is the direction in which a compass needle points at that location*. As with electric fields, we can represent magnetic fields by means of drawings with *magnetic field lines*.

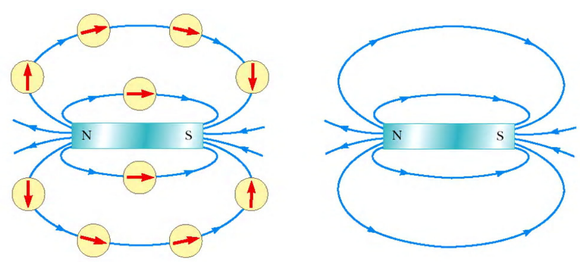


Figure 16.3.1 Plotting of Magnetic field lines of a magnet using a compass

The following are some important points to take note when representing a magnetic field by magnetic field lines:

1) Magnetic field lines appear to originate from the north pole and end on the south pole.

2) The **direction of magnetic field at any point** is indicated **by the tangent to the magnetic field line at that point**. The direction of the magnetic field at any point in space is the direction indicated by the north pole of a small compass needle placed at that point.

3) Magnetic field lines do not cross.

4) The strength of the magnetic field is proportional to the number of field lines per unit cross sectional area that passes through a surface oriented perpendicular to the lines. In other words, the magnetic field is ***stronger*** in regions where the field lines are relatively ***close together*** and ***weaker*** where they are relatively ***far apart***.

The strength of the magnetic field is quantified by what is known as the **magnetic flux density**. We will define magnetic flux density later in this chapter. The unit for magnetic flux density is Tesla (T).

16.3.2 Sources of Magnetic Fields

16.3.2.1 Earth as a Magnet

Our Earth possess a weak magnetic field. The Earth's magnetic field pattern is as if a gigantic bar magnet is embedded within it. As shown in Figure 16.3.2, the orientation of this fictitious bar magnet defines a magnetic axis for the Earth.

The location where the *magnetic axis* crosses the surface in the northern hemisphere is known as the *south magnetic pole*. The *north geographic pole* is that point where the Earth's *axis of rotation* crosses the surface in the northern hemisphere.

The south and north magnetic poles are found near the north and south geographic poles respectively. When we talk about a compass magnet having a north pole and a south pole, we should say more properly that it has a 'north-seeking' pole and 'south-seeking' pole. Since unlike poles attract, the *south magnetic pole* of earth's fictitious bar magnet is in fact the location toward which the 'north-seeking' end of a compass needle points.

The magnetic axis is not exactly aligned with the Earth's rotational axis. As a result, although the north pole of a compass needle points northward, it does not point exactly at the north geographic pole.

Also, Earth's magnetic field lines are not parallel to the surface at all points. Near the magnetic poles, the field lines are almost perpendicular to the surface of the Earth. At the magnetic Equator, the magnetic field lines are almost parallel to the surface of the earth. The angle that the magnetic field makes with respect to the surface at any point is known as the ***angle of dip or inclination***.

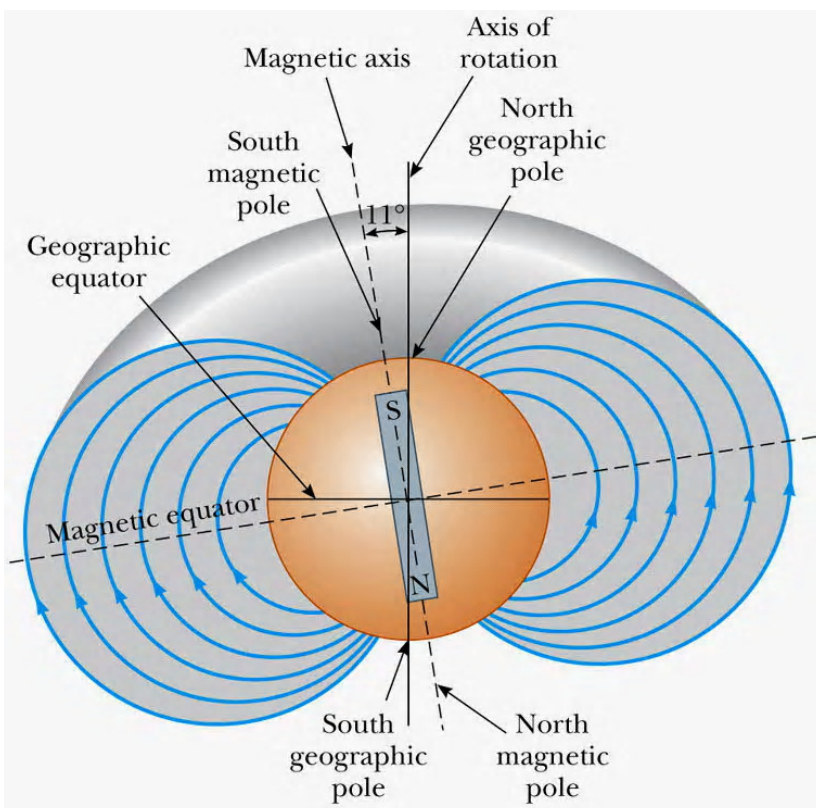


Figure 16.3.2 Earth's magnetic poles versus geographic poles

Some approximate magnitudes of magnetic fields is listed in the table:

Source	**Magnetic Flux Density (T)**
Atomic nucleus	10^{12}
Medical MRI unit	1.5
Bar magnet	10^{-2}
Surface of Sun	10^{-2}
Colour T.V.	10^{-4}
Surface of Earth	5×10^{-5}
Inside human brain (due to nerve impulses)	10^{-13}

Human exposure limit is ~0.2T.

16.3.2.2 Currents as sources of Magnetic Fields

Before the 1800s, magnetism and electricity were considered to be two independent topics. Although there was a number of scientists who thought the two topics were related, they were unsuccessful in finding the link. It was only in 1820, that a Danish physicist, Hans Christian Oersted discovered this link. He observed that a compass needle swung almost perpendicular to a current carrying conductor as if attracted by a powerful magnet.

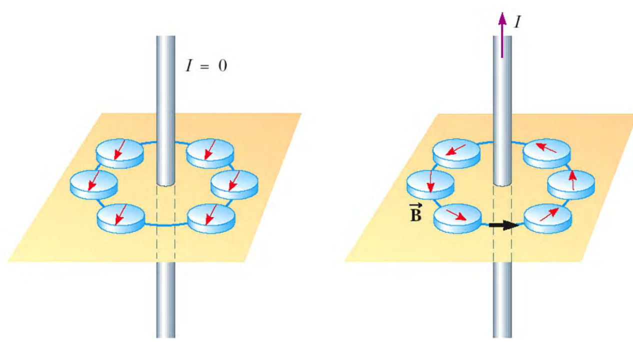


Figure 16.3.3
Compasses deflecting when the current is on.

Figure 16.3.4
Han Christen Oersted

This discovery prompted Ampere to work out the mathematical relationship between current and magnetic field known as Ampere's Law (Not required in 'A' level syllabus). It also inspired Faraday's work on electromagnetic induction. Oersted's discovery, which linked the motion of electric charges with the creation of a magnetic field, marked the beginning of an important discipline called electromagnetism.

Figure 16.3.5 Andre Marie Ampere

Figure 16.3.6 Michael Faraday

Two important observations were made about the magnetic field due to current carrying conductors:

1. The direction of the magnetic field is always _perpendicular_ to the direction of current.

2. The strength of the magnetic field produced is dependent on the magnitude of the current.

16.3.2.2.1 Long Straight Current Carrying Conductor

The magnetic field, B, at a distance, r, from a long straight wire carrying current, I, is given by

$$B = \frac{\mu_o I}{2\pi r}$$

μ_o is the ***permeability of free space*** which has the value $4\pi \times 10^{-7}$ H m^{-1}.

Thus B is _directly proportional_ to I but is _inversely proportional_ to the perpendicular distance r from the wire.

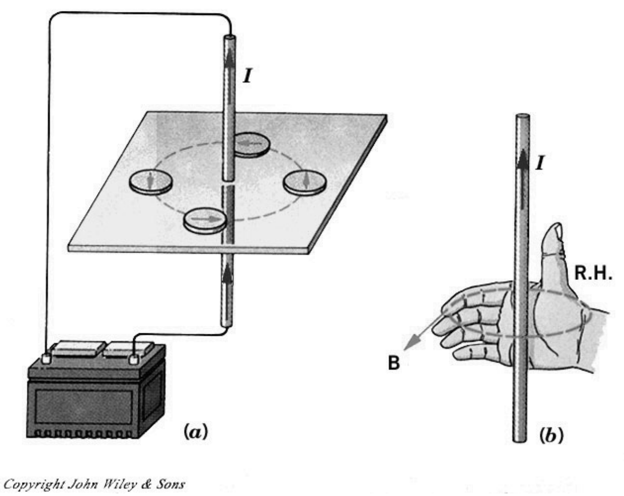
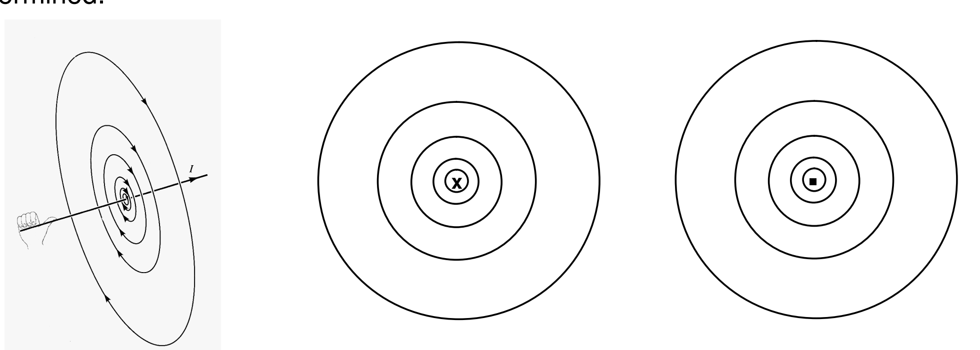


Figure 16.3.7 Magnetic Field of A Long Straight Wire

Using the right hand grip rule, the direction of the B-field produced by straight currents can be determined.



Plan view of current out of the paper

Plan view of current into the paper

Figure 16.3.8 Drawing magnetic field lines for straight wire

1. The magnetic field lines form concentric circles around the straight wire. Given a choice, *always draw the plan view.*
2. When drawing the lines, it is extremely important to show the *field lines spreading further and further apart as r increases.* This is because the B-field is getting weaker as we move away from the source (i.e. the wire).
3. The formulae given above **is not in the syllabus (i.e. no need to memorise)**. You only **need to appreciate that the *B-field is proportional to the current producing it and inversely proprtional to the distance from the source*.** If calculations are required, the formulae should be provided but symbols will not be explained in the question.

16.3.2.2.2 Circular Coils

Magnitude of the magnetic flux density at the centre of the coil is given by:

$$B = \frac{\mu_0 N I}{2r}$$

B : magnetic flux density at the center of the circular coil
I : current in the coil
μ_0 : permeability of free space
N : number of turns of coil
r : radius of the coil

We will still use the right hand grip rule to determine the direction of the magnetic field lines produced by current in circular coils. We can however deploy 2 different methods:

1. Similar to the straight current scenario, the thumb represents the current and the coiling fingers the B-field

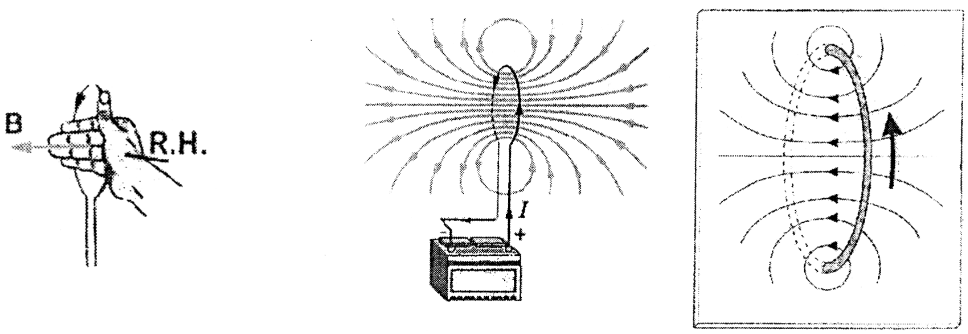


Figure 16.3.9 RHGR with thumb representing current

2. For “circular” currents, we can exchange and let the coiling fingers represent the direction of the current in the circular coils and let the thumb represent the direction of the magnetic field lines passing through the cross sectional area of the circular coils

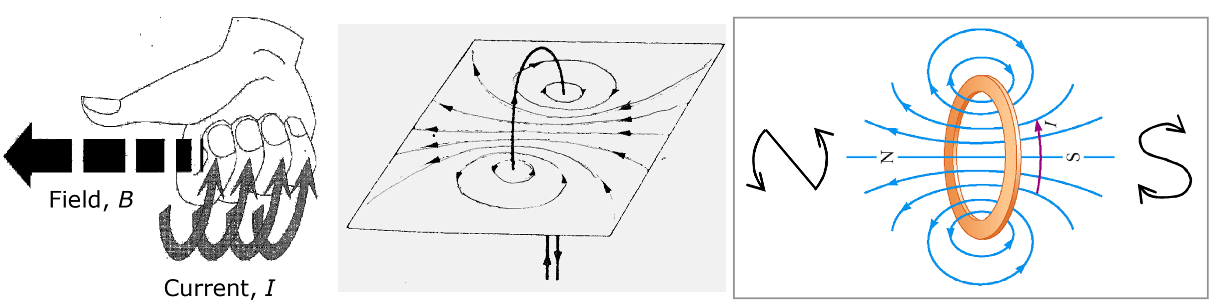


Figure 16.3.10 RHGR with the thumb representing magnetic field

1. Using the thumb to represent the B-field also allows us to determine the " North" pole of the circular coil, since B-field lines originate from the "North" pole of the magnet. This will be very useful later.
2. It is sometimes difficult to tell from the diagram which part represent the " front" of the coils. Standard conventions include using a hard line for the "front" and dotted line for the "back" and using a thicker/bolder line for the "front" of the coil.

16.3.2.2.3 Long Solenoid

The magnetic field, B, at the <u>*centre of a long solenoid*</u> with *n* turns per unit length and carrying current, I, is given by

$$B = \mu_o nI$$

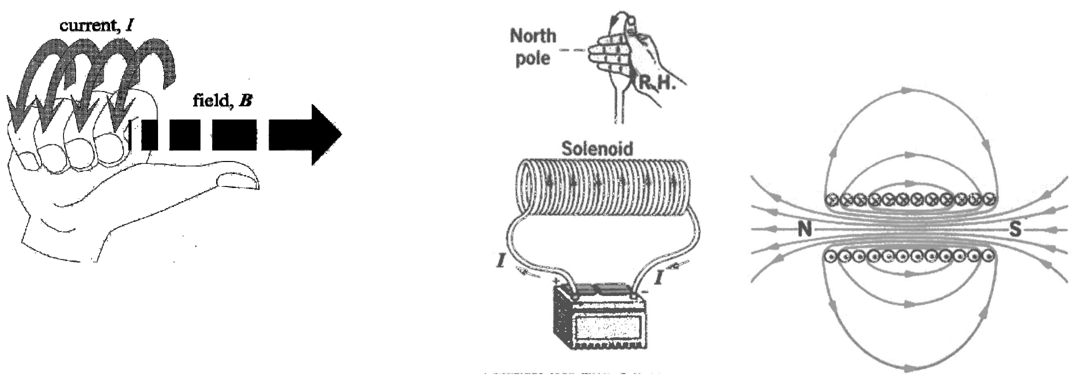
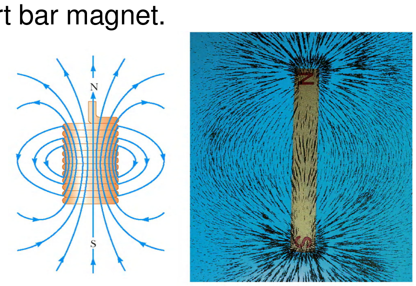


Figure 16.3.11 RHGR with the thumb representing magnetic field

1. The magnetic field produced by a long solenoid is *uniform* for the length of the siolenoid except for the ends of the solenoid. This is represented by the *parallel uniform lines along the axis of the solenoid.*
2. The solenoid also has a " North" and "South" pole. In fact, its field pattern is very similar to that of a short bar magnet.



3. The magnetic flux density *at the ends is half the magnetic flux density at the center* of the solenoid.
4. The magnetic flux density can be increased by *inserting a ferrous core* into the solenoid.

16.3.3 Permeability, μ

One way of strengthening the magnetic field of a solenoid is to insert a piece of soft iron (ferrous core) into the solenoid. The magnetic field strength at the poles of the solenoid will be modified.

$$B = \frac{1}{2}\mu_0 nI \Rightarrow B = \frac{1}{2}\mu nI$$

In this case, the soft iron, which can be permanently magnetized, increased μ_0 to μ. The magnetic domains in the soft iron causes the magnetic field to strengthen. Inserting the soft iron causes the permeability of free space, μ_0, to change to permeability of iron, μ. Materials that add to magnetic field in this manner are described as *ferromagnetic*.

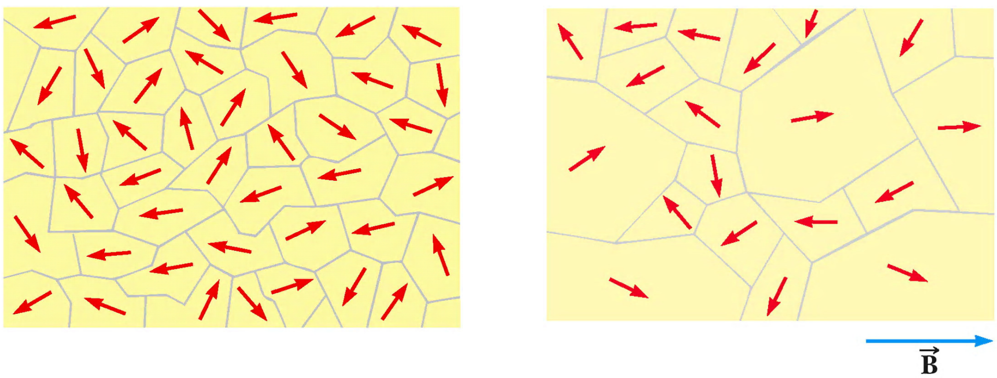


Figure 16.3.12 Aligning of magnetic domains

Examples include soft iron, steel, cobalt and nickel. They could all be magnetized.

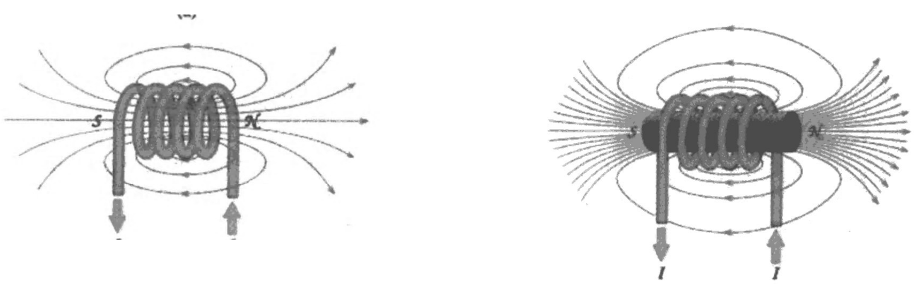
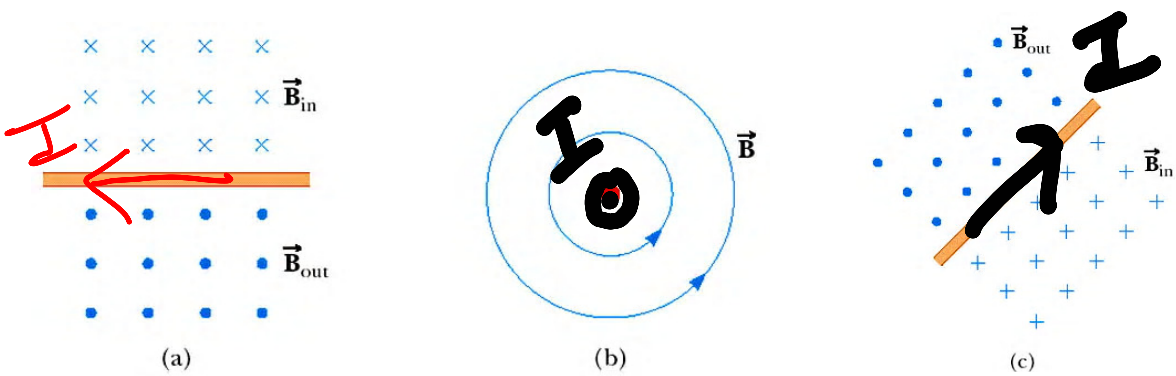


Figure 16.3.13 Increasing field lines due to ferrous core

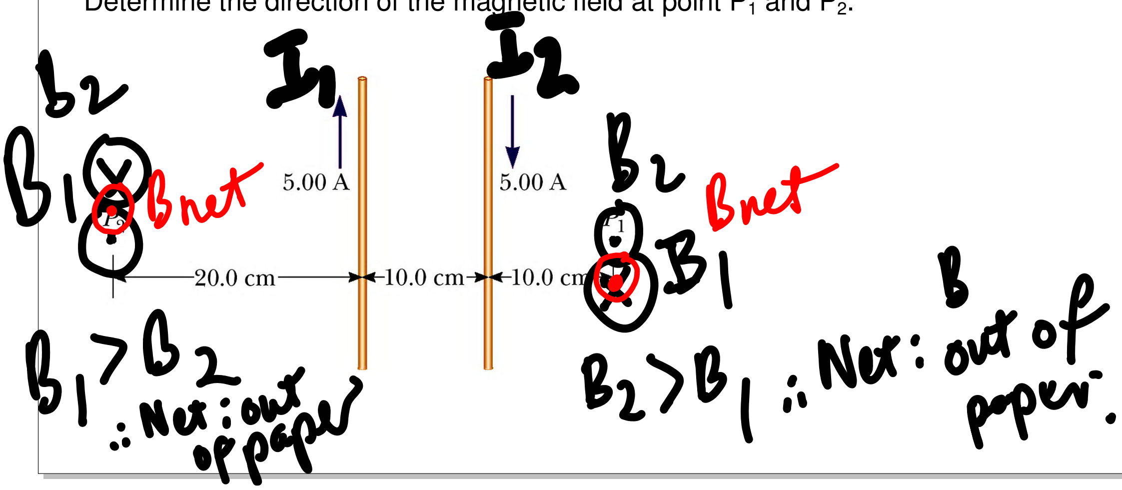
Example 1

Determine the direction of the current producing the magnetic field.



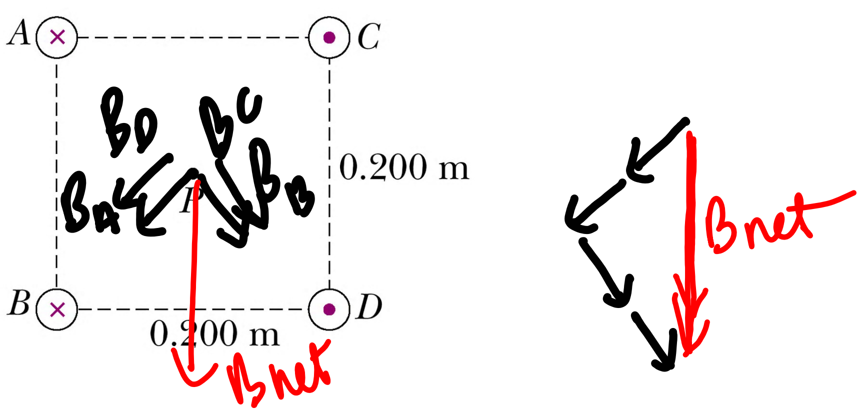
Example 2

Determine the direction of the magnetic field at point P_1 and P_2.



Example 3

Determine the direction of the magnetic field at the center of the square assuming all currents are of the same value.



16.4 Force on Current in Magnetic Field

Since current carrying wires generate magnetic fields, would these wires be attracted or repelled when place in the vicinity of permanent magnets or any magnetic field?

Looking back at the fields that you have learnt:

1. *Mass* in a *gravitational field* experiences a gravitational force *along the field*, $\vec{F} = m\vec{g}$.

2. *Charge* in an *electric field* experiences an electric force *along the field*, $\vec{F} = q\vec{E}$.

3. *Current* in a *magnetic field* experiences a magnetic force *perpendicular to both the current and the field*, $\left|\vec{F}\right| = \left|\vec{B}\right|\left|\vec{I}\right| l \sin\theta$.

16.4.1 Demonstration of Force acting on a straight current carrying conductor placed in an external magnetic field

In the last section, it was mentioned that in 1819, Oersted discovered that currents produced magnetic fields. In his experiment, he found a current carrying wire to deflect a compass nearby, meaning that the magnet in the compass experience a force due to the current carrying conductor. Hence, by Newton's third law, the current carrying wire will also experience a force due to the magnet.

We can demonstrate this quite easily using the following setup.

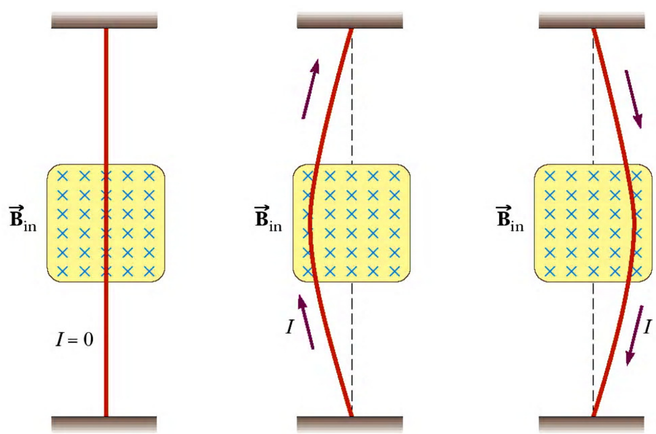


Figure 16.4.1

Consider a wire hanging between the poles of a horse shoe magnet. Using a cross sectional view, we can see that the B-field due to the magnet is directed into the page.

The following observations can be made:

1. When the current in the wire is zero, the wire hangs vertically.
2. When the wire carries a current directed upwards, the wire deflects to the left. This tells us that it experiences a force.
3. When the current is reversed, the wire deflects to the right. This tells us the force changes direction, hence the direction of the force is dependent on the direction of the current in the *B*-field.
4. When the current carrying wire is rotated, the maximum deflection occurs when the current is perpendicular to the *B*-field and there is zero deflection when the wire is parallel to the *B*-field. This tells us that the force is dependent on the orientation between the *B*-field and the current.

16.4.2.1 Calculating the Force on Current in External Magnetic Field

Previously, you have learnt that Fleming's Left Hand Rule allows you to determine the direction of the magnetic force $\boldsymbol{F}$ on a current carrying conductor placed perpendicular to a magnetic field B. However, in general, the angle between $\boldsymbol{B}$ and $\boldsymbol{I}$ can be any angle θ. $\boldsymbol{B}$ and $\boldsymbol{I}$ are two vectors lying on the same plane (Two vectors from the same point will always lie on the same plane). The magnetic force $\boldsymbol{F}$ experienced by the conductor is ***always*** **perpendicular** to **both** $\boldsymbol{B}$ and $\boldsymbol{I}$. Fleming's Left Hand Rule can still be applied in such instances to determine the orientation of F.

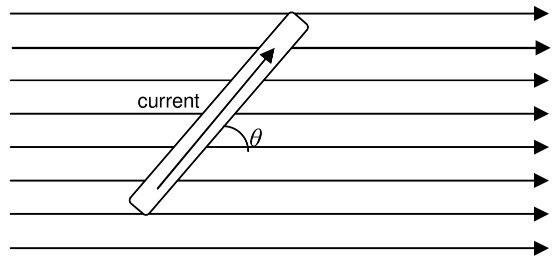
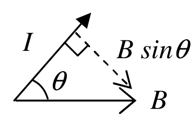


Figure 16.4.2 Magnetic Force on a Current Carrying Conductor

In the above situation, the component of the magnetic field perpendicular to the conductor is given by

$$B_{\perp} = B\sin\theta$$

where θ is the angle between B and I.



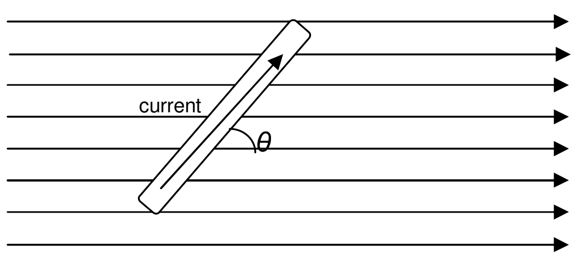
Hence, the magnetic force on the straight conductor is given by

$$\boxed{F_B = BIL\sin\theta}$$

where L is the length of the conductor carrying current, I, immersed in the magnetic field, B. θ is the angle between B and I.

The direction of the magnetic force is given by the Fleming's Left Hand Rule.

In this case,

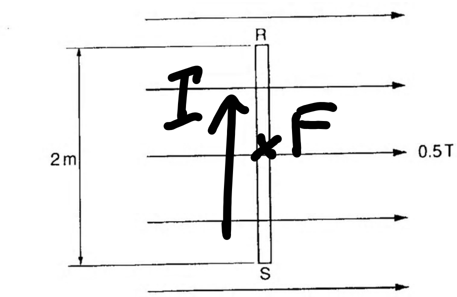


The direction of the magnetic force will be into the page.
Remember that the directions of $B_{\perp}$, I and F_B are perpendicular to each other.

If you memorise the force as $F_B = BIL\sin\theta$, please remember that the **angle θ is given as the angle between the current and the B-field.** Examiners love to trick you by giving you the wrong angle in the diagram so do watch out!

Example 4 (N98/I/19)

The diagram shows a current carrying conductor RS of length 2m placed perpendicularly to a magnetic field of flux density 0.5 T. The resulting force on the conductor is 1 N acting into the plane of the paper. What is the magnitude and direction of the current?



I

$F = BIL$

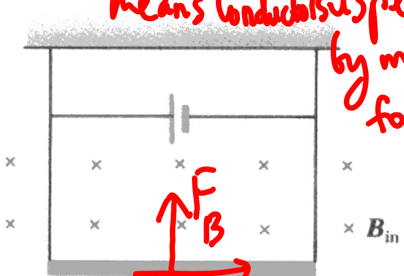
$(1) = (0.5)(I)(2)$

$I = \frac{1}{0.5 \times 2} = 1\text{ A}.$

Example 5

A conductor suspended by two light flexible wire as shown in the figure below has mass per unit length, 0.04 kg / m. What current must exist in the conductor in order for the tension in the supporting wires to be zero if the magnetic field in the region is 3.6 T into the page?

means conductor suspended by magnetic force.



$I = 0.11A$

$F = BIL$

must equal weight of conductor.

For 1m conductor:

$0.04 \times 9.81 = 3.6(I)(1)$

$I = \frac{0.04 \times 9.81}{3.6} = 0.11A$

16.4.2.2 Defining the Magnetic Flux Density and tesla

Definition of Magnetic Flux Density, B:
The magnetic flux density is defined as the force per unit length per unit current acting on an infinitely long current carrying conductor placed perpendicularly to the magnetic field.

$$B = \frac{F}{IL\sin 90^0}$$

Definition of tesla (T) :
The magnetic flux density of a magnetic field is said to be 1 tesla, if the force acting per unit length on an infinitely long conductor carrying a current of 1 A and placed perpendicularly to the magnetic field is 1 N m^{-1}.

16.4.2.3 Forces between 2 long parallel current carrying conductors

When 2 parallel infinitely long wires are placed in a vacuum, each wire experiences a force due to the other.

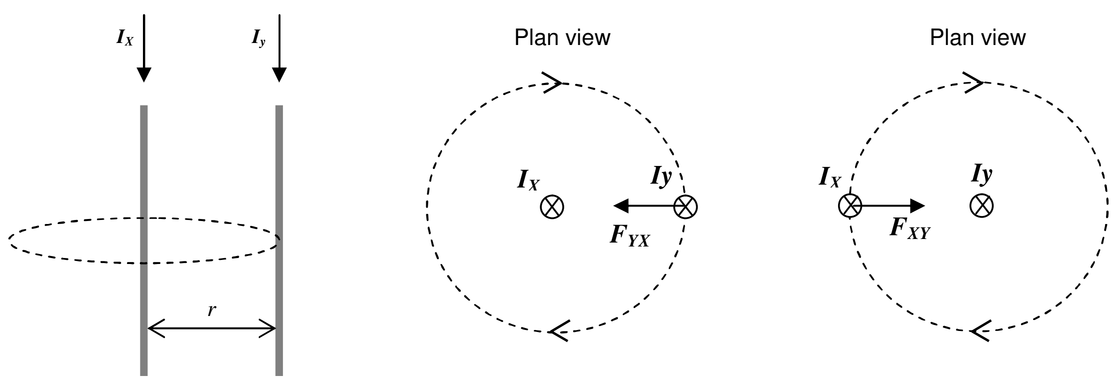


Figure 16.4.3

The current I_X sets up a magnetic field that interacts with current I_Y. Therefore the force acting on I_Y due to B_X is $F_{YX} = B_X I_Y l$

Recall that B_X is given by $$B_X = \frac{\mu_0 I_X}{2\pi r}$$

Hence the force $$F_{YX} = \frac{\mu_0 I_X I_Y l}{2\pi r}$$

Formula not in syllabus

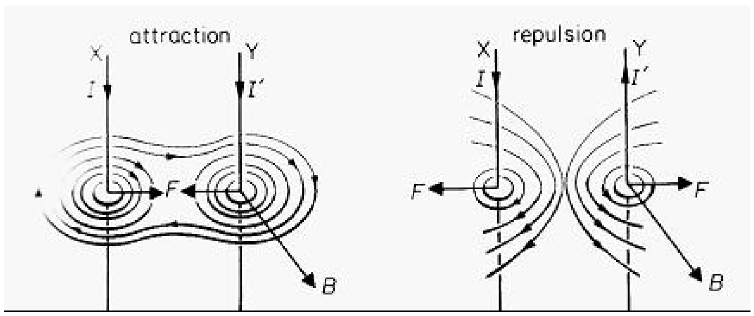
The direction of the force on I_Y can be found using Fleming's Left Hand Rule. In this case, the force on I_Y due to I_X is towards I_x. We can go through the same analysis to understand the force acting on I_X as a result of I_Y, but honestly, there is no need to do so. This is because we can simply apply Newton's 3rd law and conclude that the force on I_X due to I_Y is of the same magnitude but in opposite direction!

Hence the force on I_X due to I_Y is also $F_{XY} = \dfrac{\mu_0 I_X I_Y l}{2\pi r}$. } Formula not in syllabus

It is interesting to note that in this case where the two currents are flowing in the same direction, the force between them is attractive, We can apply a similar analysis to currents flowing in the opposite directions and find that the force between them is repulsive.

A simple way of remembering the conclusion is

"LIKE CURRENTS ATTRACT, UNLIKE CURRENTS REPEL."



Chapter Connection:
Do you remember the definition for Ampere?
The above equation is actually the basis for the definition of Ampere. Consider 2 straight infinitely long current carrying conductor placed at a distance r = 1 m apart. If the currents flowing in each wire is 1A, then the force per unit length acting on each conductor would be given by

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi r} = \frac{(4\pi \times 10^{-7})(1)(1)}{2\pi(1)} = 2\times 10^{-7}\ \text{N m}^{-1}$$

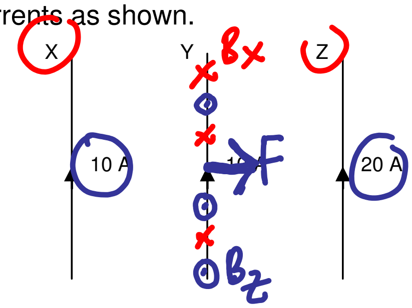
Hence the definition of Ampere:
The ampere (1 A) is defined as the value of the constant current of two straight infinitely long current carrying conductors, when placed 1 m apart will produce a force per unit length of 2 x 10^{-7} N m^{-1} between them.

weaker attractive force

stronger attractive force

Example 6

X, Y and Z are three coplanar long parallel wires carrying currents as shown.



The resultant force on wire Y is

A zero

B towards X

C towards Z

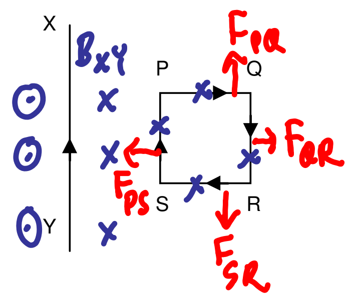
D perpendicular to the paper

$B_x < B_z$

$\therefore B_{net}$ out of paper

Example 7

A long straight wire XY lies in the same plane as a square loop of wire PQRS which is free to move. The sides PS and QR are initially parallel to XY. The wire and loop carry steady currents as shown in the diagram.



What will be the effect on the loop?

A It will move towards the long wire.

B It will move away from the long wire.

C It will rotate about the axis parallel to XY.

D It will be unaffected.

E It will contract.

Recall: $B_{XY} \propto \frac{I_{XY}}{r}$ $\therefore F_{PS} > F_{QR}$

$F_{PQ} = F_{SR}$

$\therefore F_{net} \leftarrow$.

16.4.2.4 DC Motor Refer to powerpoint slides (section on DC motor)

Consider a rectangular coil *PQRS* of N turns pivoted so that it can rotate freely about a vertical axis which is perpendicular to a uniform horizontal magnetic field of flux density B. Let the normal to the plane of the coil make an angle θ with the field.

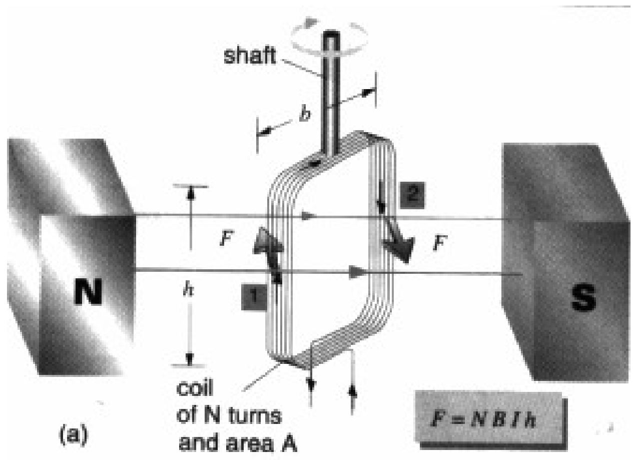


Figure 16.4.5 (a)

The side PS of length *h* is perpendicular to the magnetic field (from N to S) and so the magnetic force on it is given by

$$F = BIh$$

If the coil has N turns, the length of the conductor is increased N times, and so the force acting on side PS is

$$F = NBIh$$

The force acting on side QR is also given by $F = NBIh$, but its direction is opposite to that on PS, as shown in Figure 16.4.5 (b). There are no forces on sides PQ and SR although they carry currents because PQ and SR are parallel to the magnetic field.

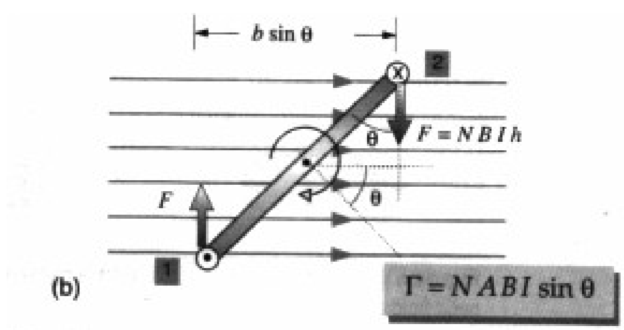


Figure 16.4.5(b)

The two forces on sides PS and QR tend to turn the coil about an axis XY passing through the middle of the coil. These two forces together are called a couple and the torque due to this couple is given by

$$\tau = F(b\sin\theta) = NBIhb\sin\theta$$

But $h \times b$ = Area, A of the coil. So

$$\tau = BANI\sin\theta$$

16.4.3 Measuring Magnetic Flux Density using a Current Balance

With the aid of the diagram given, show how magnetic force due to a current can be measured. (Hint: use conditions for equilibrium) Having measured the magnetic force, what other measurements will you take to deduce the magnetic flux density?

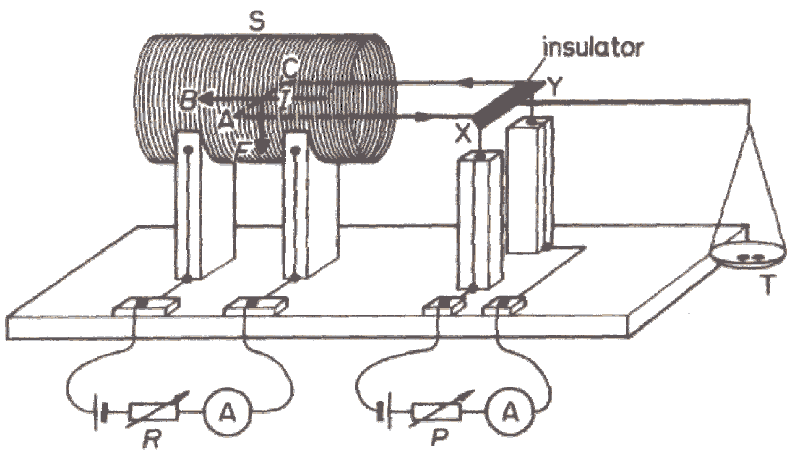


Figure 16.4.6 Current Balance

<u>Principle of a Current Balance:</u>

1. A wire frame AXYC is balanced on 2 knife edges through which a current *I* can pass from a battery.

   The frame is arranged such that the side AC of the frame (of length *l*) lies within the magnetic field whose flux density *B* is to be determined.

2. When there is no current, the frame is horizontal, as the force acting on AC is zero.

   When current flows through, a magnetic force acts on AC and pushes that side of the frame downwards (by Fleming's Left Hand Rule).

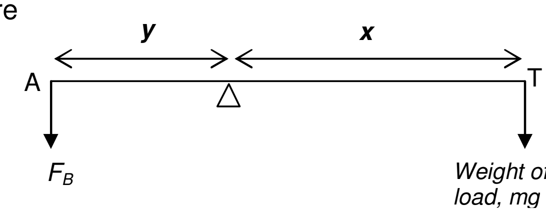
3. A known mass is loaded on the right side to restore the frame to its horizontal position.

4. Consider the free body diagram of the wire frame, taking moments about the knife edges,

   Clockwise moments = anti clockwise moments

   $(mg)\,x = (BIl)\,y$

   $$B = \frac{mgx}{Ily}$$



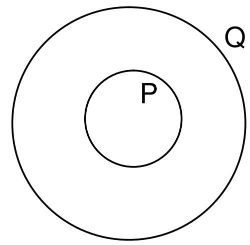
Side view of wire frame

Tutorial 16A: Magnetic Force and Magnetic Fields

Self Practice Questions:

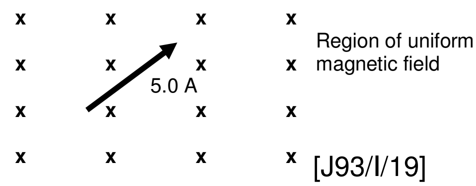
1. Define magnetic flux density and the Tesla.

2. Two circular coils P and Q lie in the same plane and are concentric. Coil P has 10 turns of radius 4 cm and carries a current of 1.0 A. Coil Q has 20 turns of radius 12 cm and the current in it is adjusted in magnitude and direction so that the resultant field at the common centre is zero. What is the current in Coil Q? [N82/II/20].



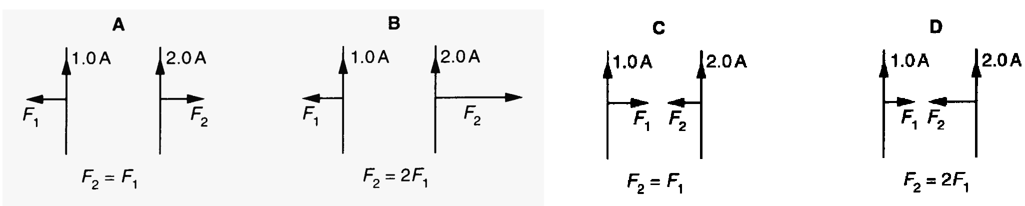
3. A wire of length 3.0 cm is placed at right angles to a magnetic field of flux density 0.040 T. The wire carries a current of 5.0 A. What is the magnitude of the force which the field exerts on the wire?

   A less than 0.006 N
   B 0.006 N
   C greater than 0.006 N but less than 0.6 N
   D 0.60 N
   E greater than 0.60 N

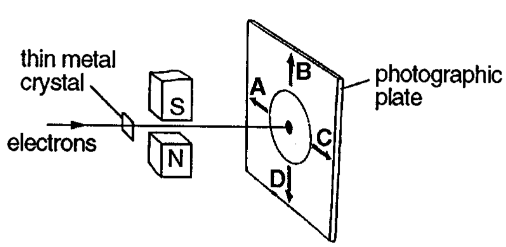


[J93/I/19]

4. Two long, straight parallel wires carry currents of 1.0 A and 2.0 A. Which diagram shows the directions and relative magnitudes F_1 and F_2 of the forces per unit length on each of the wires? [N96/I/18]



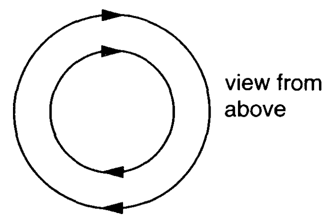
5. G P Thomson's early experiments on the diffraction of electrons by crystals were criticised on the grounds that the beams affecting the photographic plates might be X-rays. He proved that this was not so by placing bar magnets, on each side of the beam as shown in the diagram. How would the magnetic field due to the magnets affect the diffraction ring?



   A The ring would deflect in the direction of A.
   B The ring would deflect in the direction of B.
   C The ring would deflect in the direction of C.
   D The ring would deflect in the direction of D.

[N90/I/19]

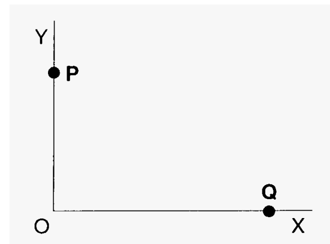
6. A small flat circular coil lies inside a similar larger coil. Each coil carries a current as shown. What is experienced by the small coil due to these currents?



A a torque about the horizontal axis
B a torque about the vertical axis
C a vertical force along the axis
D no resultant force [N00/I/18]

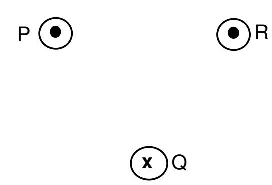
Discussion Questions:

7. The diagram shows a flat surface with lines OX and OY at right angles to each other. Which current in a straight conductor will produce a magnetic field at O in the direction OX?

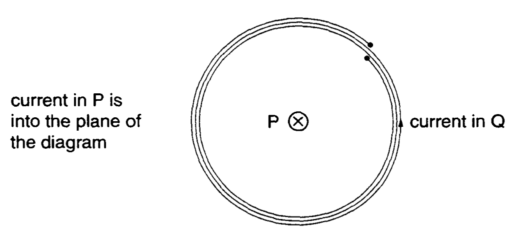


A at P into the plane of the diagram
B at P out of the plane of the diagram
C at Q into the plane of the diagram
D at Q out of the plane of the diagram [J00/I/19]

8. Three long vertical wires pass through the corners of an equilateral triangle POR. They carry equal currents into or out of the paper in the directions shown. Draw an arrow to represent the resultant force on the wire Q. [N93/I/16]



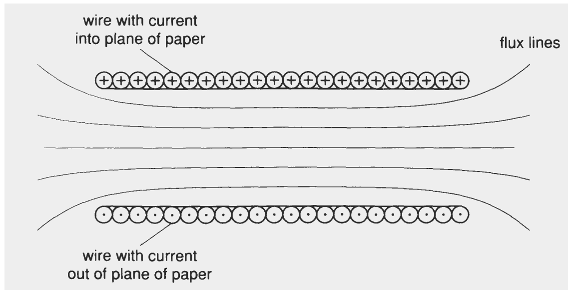
9. A long straight wire P is placed along the axis of a flat circular Q. The wire and the coil each carry a current as shown.



What can be deduced about the force acting on each part of Q due to the current P?

A The force is away from P.
B The force is towards P.
C The force is perpendicular to the plane of the diagram.
D There is no force in any direction. [J99/I/19]

10. The diagram illustrates the pattern of the magnetic flux due to a current in a solenoid.

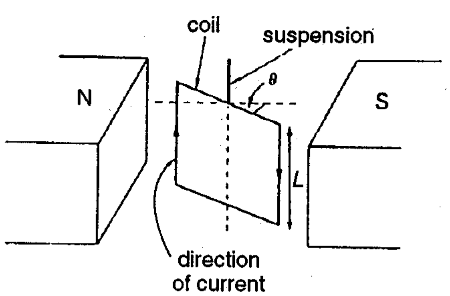


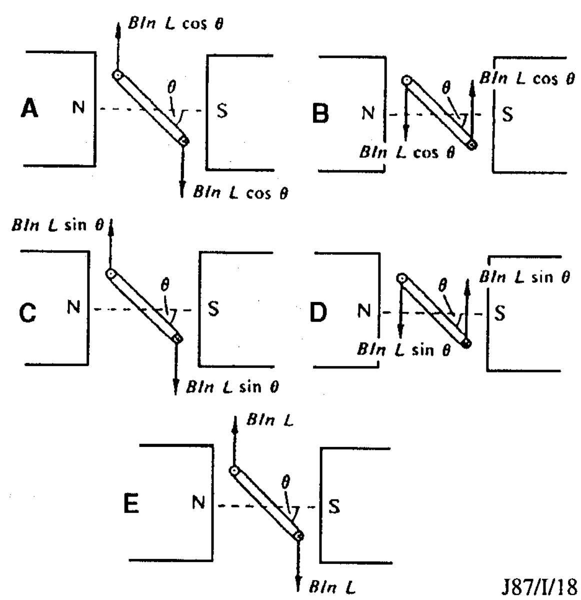
(i) Draw arrows to show the direction of the magnetic field in the solenoid

(ii) Draw a line to represent a current carrying conductor in the magnetic field which does not experience a force due to the magnetic field. Label the conductor **C**.

(iii) The coils of wire on an electromagnet are usually wound on a ferrous core. State two properties of the core which are important in its use as a electromagnet. [J97/II/3]

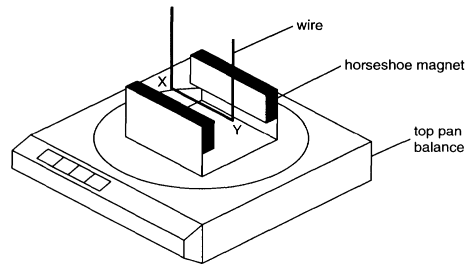
11. A current I is carried by a square coil of n turns and side L suspended vertically as shown in a uniform horizontal magnetic field of flux density B. Which one of the plan diagrams correctly shows the magnitude and direction of the forces acting on the vertical sides of the coil?





J87/I/18

12. N00/I/19: A horseshoe magnet rests on a top-pan balance with a wire situated between the poles of the magnet. With no current in the wire, the reading on the balance is 142.0 g. With a current of 2.0 A in the wire in the direction XY, the reading changes to 144.6 g. What is the reading on the balance, when there is a current of 3.0 A in the wire in the direction YX?



13. J95/II/4: A long length of aluminum foil ABC is hung over a wooden rod as shown in Fig. 21. A large current is momentarily passed through the aluminum foil in the direction ABC, and the foil moves. The foil is not damaged.

a) Draw arrows to indicate the directions in which AB and BC move.
b) Explain, in terms of physical principles, why the foil moves in this way.

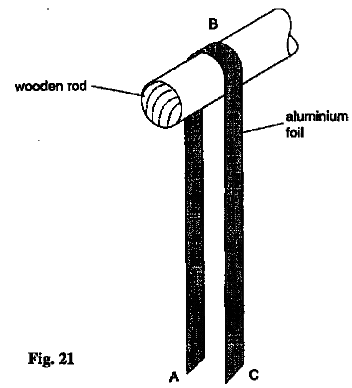
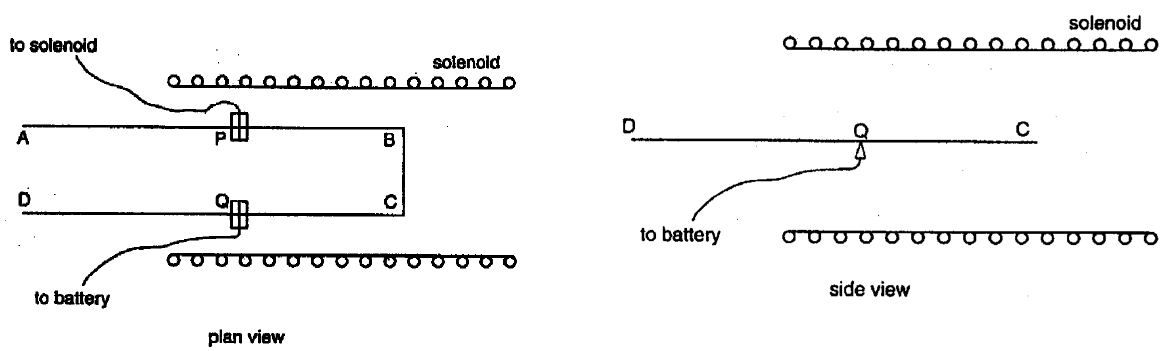


Fig. 21

14. N94/II/4: A wire frame ABCD is supported on two knife-edges P and Q so that PBCQ of the frame lies within a solenoid. Electrical connections are made to the frame through the knife-edges so that the part PBCQ of the frame and the solenoid can be connected in series with a battery. When there is no current in the circuit, the frame is horizontal.



a) When the frame is horizontal and a current passes through the frame and solenoid, what can you say about the direction of the force, if any, due to the magnetic field of the solenoid acting on
   i. side BC
   ii. side PB?
b) State two ways in which you could reverse the direction of the force on the side BC.
c) The solenoid has 700 turns m^{-1} and carries a current carrying 3.5 A. Given that the magnetic flux density B on the axis of a long solenoid is $B = \mu_0 nI$
   i. Calculate the magnetic flux density in the region of side BC of the frame.
   ii. Side BC has length 5.0 cm. Calculate the force acting on BC due to the magnetic field in the solenoid.

iii. A small piece of paper of mass 0.10 g is placed on the side DQ and positioned so as to keep the frame horizontal. Given that QC is of length 15.0 cm, how far from the knife-edge must the paper be positioned?

Solutions for 16A:

2. 1.5 A, opposite direction of current in P

3. B

4. C

5. A

6. D

7. B

9. D

11. E

12. 138.1g

14. c) (i) 3.08×10^{-3} T (ii) 5.39×10^{-4} N (iii) 8.24 cm.

16.5 Magnetic Force on a Moving Electric Charge

Previously, we learned that the magnetic force experience by a current carrying conductor in a magnetic field is given by

$$F_B = B\,I\,L\,\sin\theta$$

Since current I is the amount of charges that passed a section of the conductor per unit time,

$$I = \frac{Q}{t}$$

If L is the displacement covered by a charge Q in time t, then the velocity of the charge is given by

$$v = \frac{L}{t}$$

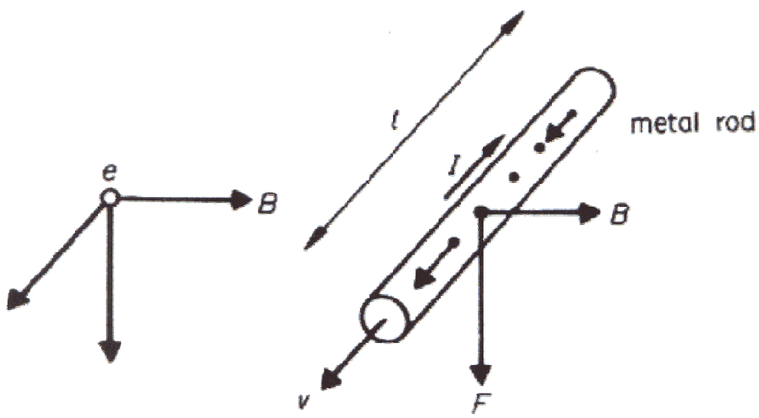


Figure 16.5.1 Magnetic Force on a Moving Charge

Hence, the magnitude of the force acting on a charge Q moving with velocity v in a magnetic field of flux density B is given by

$$\boxed{F_B = B\,Q\,v\,\sin\theta}$$

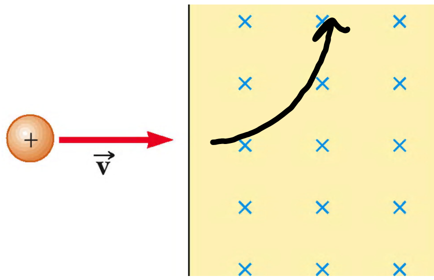
where θ is the angle between v and B.

Note:
1. The magnetic force is maximum when the charge is moving perpendicularly to the magnetic field.
2. A charge in a magnetic field does not experience any force when
   - It is moving along the direction of the magnetic field
   - It is stationary in the field

16.5.1.1 Motion of a Charged Particle in a Uniform Magnetic Field

Let's now look at how moving charges that are not confined within a wire is affected by a magnetic field. We will again use Fleming's Left Hand Rule to find the direction of this force.

Consider a positive charge entering a magnetic field with velocity *v*.



Using Fleming's Left Hand Rule and using the concept that the direction of the convention current is the direction of motion of the postive charge, we can conclude that the direction of the force at this instant is upwards. This cause the charge to be deflected.

However, note that the direction of the force is always perpendiculr to the direction of velocity and magnetic field (by virtue of Fleming's Left Hand Rule), hence the charge will move in a circular path! The magnetic force is providing for the centripetal force and accelaration of the charge.

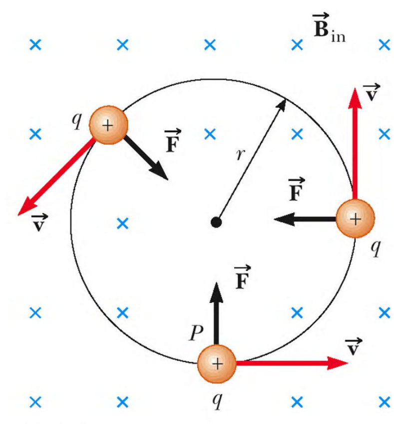


Figure 16.5.2 A moving charge performing circular motion in a magnetic field

By equating the magnetic force to the centripetal force, we obtain

$$F_B = F_C$$

$$Bqv = \frac{mv^2}{r}$$, where r is the radius of the circular path

$$r = \frac{mv}{Bq}$$

From this equation for the radius of the path, we can deduce that for particles entering the magnetic field with the same velocity, the radius would be proportional to the ratio of the mass to the charge (i.e. $\frac{m}{q}$). This ratio is known as the *specific charge*.

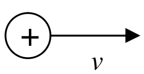
If T is the time taken to complete one revolution of the circular path and v is the constant speed of the charge,

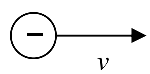
$$v = r\omega$$
$$v = r\frac{2\pi}{T}$$
$$v = (\frac{mv}{Bq})\frac{2\pi}{T}$$
$$T = \frac{2\pi m}{Bq}$$

The period T is dependent on the mass, magnetic flux density and the charge of the particle. It is independent of the speed of the particle or the radius of the circular path.

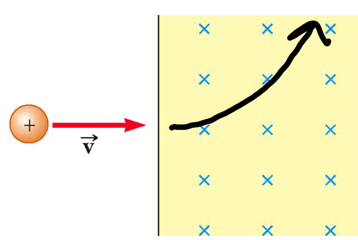
1. Similar to the force acting on straight current carrying conductor placed in the magnetic field, we have to remember that the *angle θ is the angle between the direction of motion and the magnetic field lines*. This is a similar trick used by examiners.

2. For negative charges moving a magnetic field, the magnitude of the force is still the same. However, when determining the direction of the force, we have to remember to use the *direction of convention current for Fleming's Left Hand Rule. Hence for positive charge, the direction of I is the direction of v, but for negative charge, the direction of I is opposite to the direction of v.*





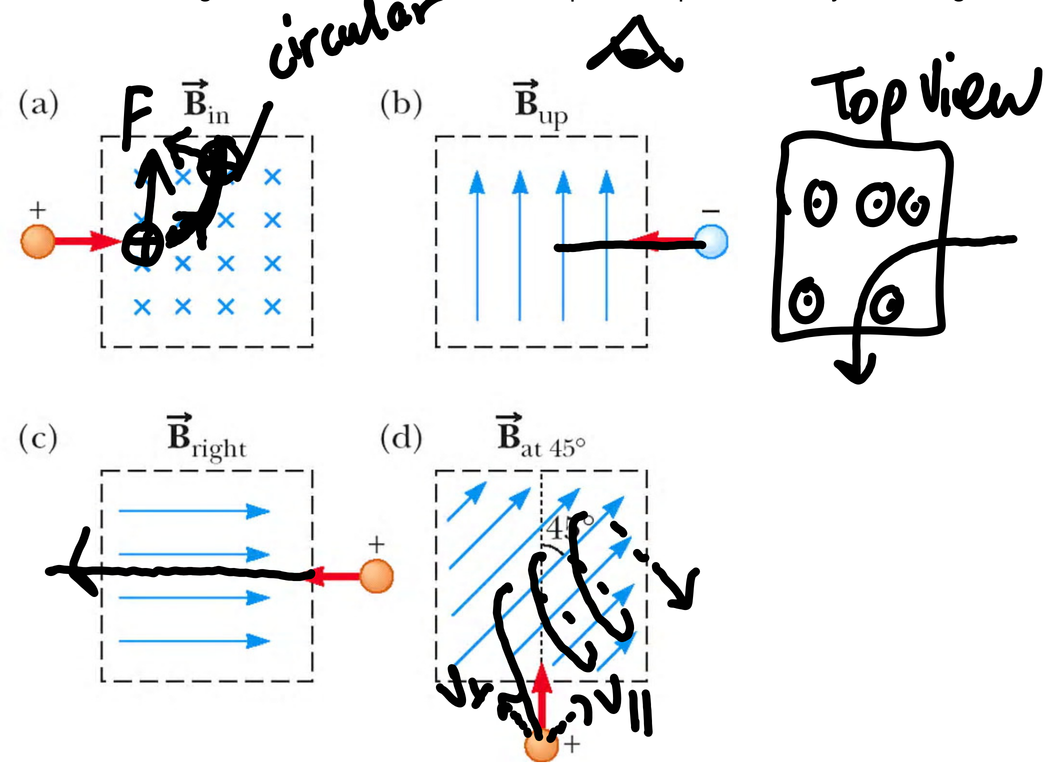
3. It is very common in exam questions to be asked to draw the path taken by moving charges in a magnetic field. Simply apply Fleming's Left Hand Rule (remember the sign of the charge is important!) and the direction of the magnetic force is also the direction of the centripetal force. The centripetal force acts towards the center of the circular motion, and hence deflect the moving charge in the direction of the force, or imagine where the center of the circular motion is, and you should be able to draw the path correctly. Please ensure that the path is as circular as possible, that is, you should draw with a set of compass. If you really don't have one in the exam, then label the path drawn as 'circular path'.



4. The magnetic force does no work on the charge as it is perpendiular to *v*. Hence, the speed and kinetic energy of the charge remains the same as it moves along the circular path.

Example 8

Determine the direction of the magnetic force. Hence, sketch a possible path taken by the charged particle.



Example 9

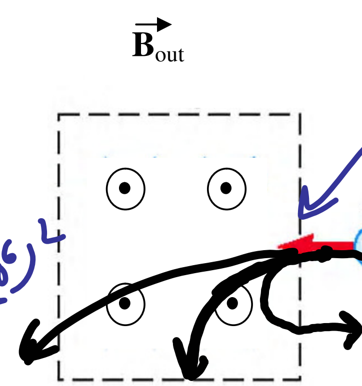
An electron with speed 2.0 x 10^6 m s^{-1} enters a magnetic field of flux density 2.0 mT perpendicular to its direction of motion. The magnetic field only exists within a square of size 8.0 mm. Draw the path taken by the electron as its moves through the magnetic field.

$$F_{net} = \frac{mv^2}{r}$$

$$Bqv = \frac{mv^2}{r}$$

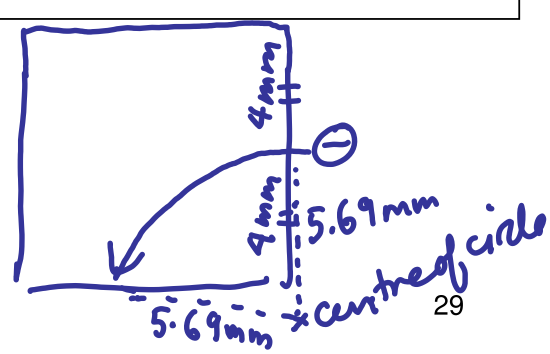
$$2.0\times10^{-3} \times 1.6\times10^{-19} \times 2.0\times10^{6} = \frac{9.11\times10^{-31}\times(2.0\times10^{6})^2}{r}$$

$$r = 0.005693\text{ m}$$
$$\simeq 5.69\text{ mm}$$



one of this path, depends on r.

ANS :



Tutorial 16B: Magnetic Force on A Moving Electric Charge

Self Practice Questions:

1. There are two situations in which a charged particle in a magnetic field does not experience a magnetic force. State these two situations.

2. A charged particle is situated in a region of space and it experiences a force only when it is in motion. It can be deduced that the region encloses

   A both an electric and gravitational field
   B both a magnetic and an electric field
   C both a magnetic and a gravitational field
   D a magnetic field only
   E an electric field only [J89/I/26]

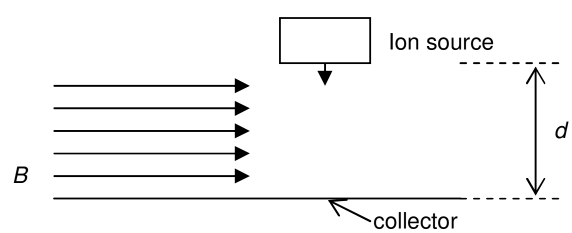
3. An electron of mass m_e, and charge e moves in a vacuum with uniform speed v. A uniform magnetic field of flux density B acts perpendicular to the direction of v.
   a) Explain why the electron moves in a circular orbit and show by means of a careful sketch the direction of its rotation relative to the direction of B.
   b) Find an expression for the radius of its orbit in terms of v, B e and m_e.
   c) Hence show that the time taken to complete one revolution in the orbit is given by

$$t = \frac{2\pi m_e}{Be}$$

[J87/I/14]

Discussion Questions:

4. An ion source is at distance d from a flat, horizontal collector at the same potential as the source. A magnetic field of flux density B acts horizontally as shown in the diagram. The field is uniform throughout the region between the source and the collector.

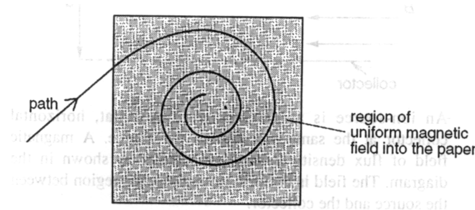


An ion of charge q and mass m is emitted vertically downwards at speed v. Under what conditions will the ion reach the collector?

A $v > \sqrt{\frac{2Bq}{m}}$ B $v < \sqrt{\frac{2Bq}{m}}$ C $v = \sqrt{\frac{dBm}{q}}$ D $v > \frac{dBq}{m}$

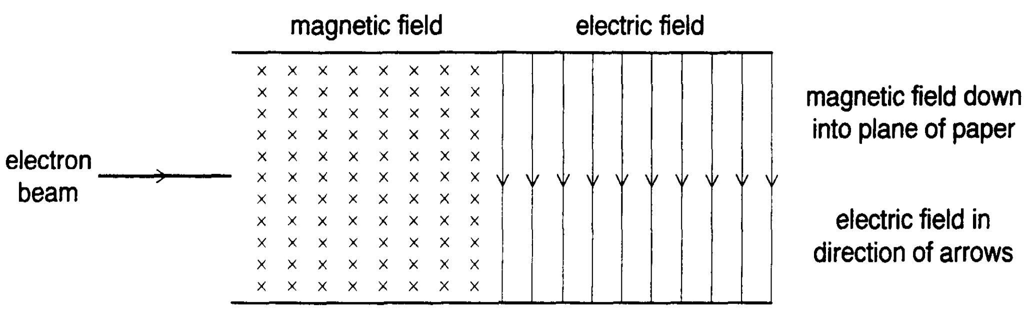
E $v < \frac{dBq}{m}$ [J88/I/27]

5. A common way of investigating charged particles is to observe how they move in a plane at right angles to a uniform magnetic field. The diagram shows the path of a certain particle. Which of the following gives a satisfactory explanation for the path?



A The momentum of the particle is increasing steadily.
B The charge on the particle is decreasing steadily.
C The magnetic flux density is decreasing steadily.
D The mass of the particle is increasing steadily.
E The speed of the particle is decreasing steadily. [N93/I/26]

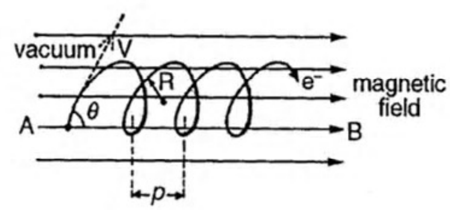
6. While travelling between an anode and the screen of a cathode ray tube, electrons move through adjacent electric and magnetic fields as shown.



On the diagram, sketch a possible path of an electron through both fields [J99/II/6part]

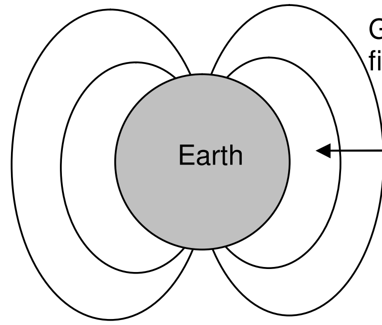
7. Describe the shape of the paths followed by electrons injected
   i. at right angles into a uniform magnetic field,
   ii. at right angles into a uniform electric field

b) An electron is injected at a speed v of 7.0 x 10^6 m s^{-1} at an angle θ into a uniform magnetic field of flux density 3.14 x 10^{-5} T. It describes a helical path as shown in the diagram. Assuming that sin θ = 0.6 and cos θ = 0.8, show that the velocity component of the electron perpendicular to the field is 4.2 x 10^6 m s^{-1}.



c) Hence calculate
   i. the radius of the helical path
   ii. the time taken for the electron to complete one revolution in the helix
   iii. the velocity component of the electron parallel to the field
   iv. the pitch, p, of the helix

8. Cosmic rays are charged particles emitted by stars and they travel at very high speeds. These particles bombard the earth all the time. The majority of these particles are protons traveling close to the speed of light. A proton moves in the direction towards the earth as shown in the diagram.
   a) Find the direction of the magnetic force acting on the proton.
   b) Explain how the Earth is shielded from the protons by the geomagnetic field.
   c) Hence, explain which parts of the Earth are least shielded from the protons.



Solutions for 16B:

1. Stationary charge. Charge moving parallel to the magnetic field lines

2. D

3. $r = m_e v/(Bq)$

4. D

7. c) i. 0.762 m   ii. 1.14 μs   iii. 5.6×10^6 m/s   iv. 6.38 m

16.5.2 Moving charges in E and B fields

It is possible for a charge to move into a region where both an electric field and a magnetic field are applied. The charge will experience an electric force and a magnetic force simultaneously. To determine the final motion of the charge, we will have to go back to Newton's laws of motion which helps us to predict the motion once we know the resultant force acting on the charge. Since we have just covered how a magnetic field exerts a force on a moving charge, we will take a few moments to recap how an electric field affects a moving charge.

16.5.2.1 E-field concepts (Recap)

- Magnitude of the electric force:

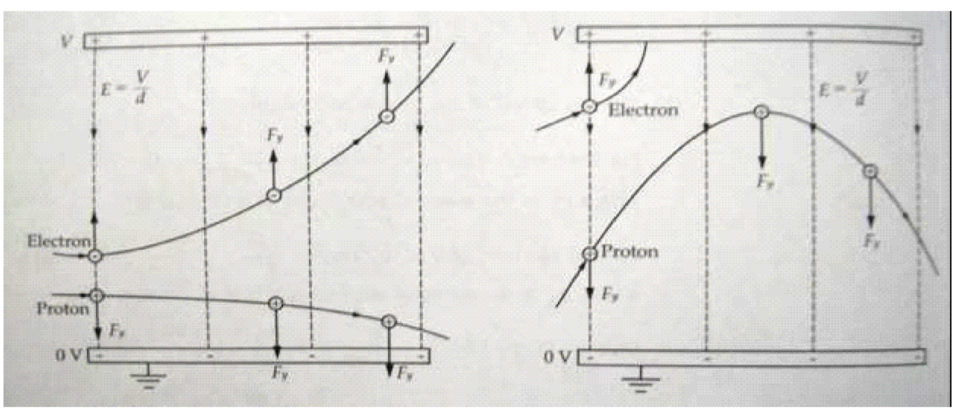
$$\boxed{F_E = qE}$$

  where q is the magnitude of the charge and E is the electric field strength.

  Note: the electric force is independent of the motion of the charge. More specifically, a stationary charge will experience an electric force, but a stationary charge will not experience a magnetic force.

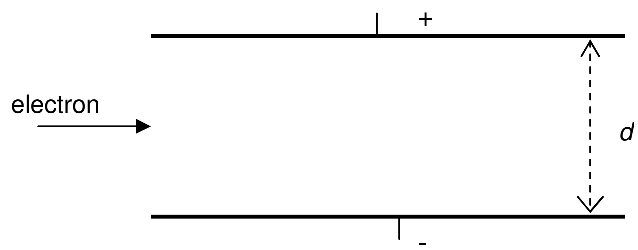
- Direction of the electric force:
  The direction is also dependent on the sign of the charge.
  For a <u>positive</u> charge, the direction of the electric force is <u>in the direction</u> of the E field.
  For a <u>negative</u> charge, the direction of the electric force is <u>opposite</u> to the direction of the E field.

  The diagram below shows the trajectories of a proton and electron moving in opposite directions in the same electric field. The radius of curvature for the proton is larger because its mass is about 2000 times bigger than the mass of the electron.



- Deflecting a moving charge in a uniform electric field

Consider an electron moving into a uniform E-field set up by a pair of parallel plates.



The electron experiences a constant electric force that that is directed opposite to the E-field. If this is the only force exerted on the electron, then it must be the resultant force and cause the electron to accelarate according to Newton's 2nd law of motion.

$$\Sigma F_y = ma_y$$

$$qE = ma_y$$

If the potential difference between the plates is *V* and their separation is *d*, the accelaration of the electron will be given by

$$a_y = \frac{qE}{m} = \frac{qV}{md}$$

Since the acceleration is constant, we can apply the equations of kinematics in 2D. In this case, the horizontal component of the velocity remains a constant, while the vertical component of the velocity undergoes uniform accelerated motion. The combined result is of course projectile motion. This is analogous to the situation of a ball moving at an angle to a uniform gravitational field.

1. Note that we have neglected the gravitational force acting on the electron. This is a good approximation when we are dealing with atomic particles. For an electric field of 10^4 N C^{-1}, the ratio of the magnitude of the electric force *qE* to the magnitude of the gravitational force *mg* is on the order of 10^{14} for an electron and 10^{11} for a proton.
2. The electron only experiences a electric force when in the E field. Once it leaves the E field set up by the parallel plates, it will obey Newton's first law of motion and continue to move in a straight line at constant speed. When asked to draw the path, label "parabolic" or "projectile" within the E-field and make sure that the point where it leaves the E field, the path must be tangent to the parabolic path, then straight line.

The table below summarizes the differences in the deflection of chargaes in a magnetic and electric field.

Deflection in a magnetic field	Deflection in an electric field
1. The magnetic field can exert a magnetic force only on a moving charged particle. Stationary charged particles experience no force.	1. The electric field always exerts an electric force on a charged particle, whether it is stationary or moving.
2. The magnetic force is perpendicular to the magnetic field and the direction of motion of the charged particle. Deduced from Fleming's Left Hand Rule.	2. The electric force acts in the direction of the electric field. Deduced from the law of electrostatics (i.e. Like charges repel; unlike charges attract.)
3. Magnetic force is dependent on the speed and direction of motion of the charged particle. ($F_B = Bqv\sin\theta$)	3. Electric force is not dependent on the speed and direction of the charged particle. ($F_E = qE$)
4. Circular motion is obtained when a charged particle enters a magnetic field perpendicularly.	4. Parabolic motion is obtained when a charged particle eneters an electric field perpendicularly.

16.5.2.2 Velocity Selector

In many experiments involving moving charged particles, it is important that the particles all move with essentially the same speed. This can be achieved by applying a combination of an electric field and a magnetic field oriented as shown in the figure below.

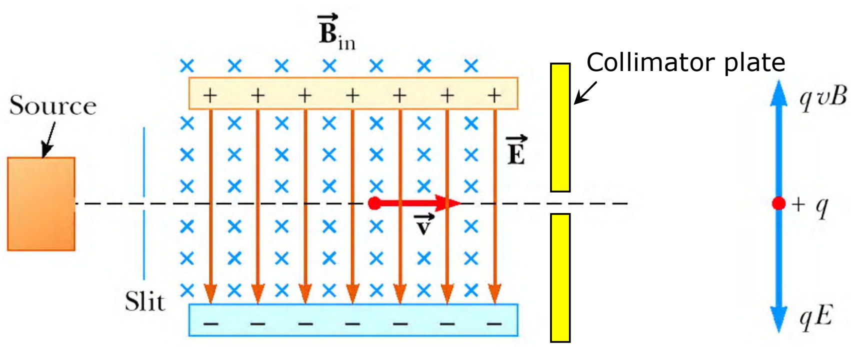


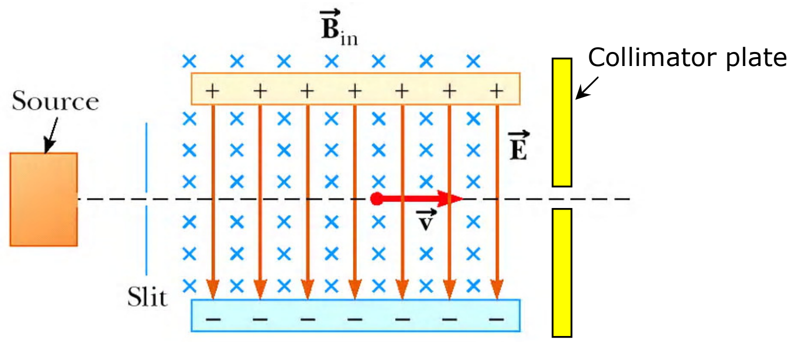
Figure 16.5.8

A uniform E field is applied vertically downwards and a uniform magnetic field is applied in the direction perpendicular to the electric field. Consider a positive charge entering the region from the right with velocity v.

It experiences a electric force qE that is downwards (in the same direction as the electric field) and a magnetic force Bqv that is upwards (Fleming's Left Hand Rule). By adjusting the magnitudes of the electric and magnetic fields, we can set up a scenario so that $qE = Bqv$ and the particle experiences no resultant force, and moves through the fields in a straight horizontal line!

$$\Sigma F = 0$$
$$F_B = F_E$$
$$Bqv = qE$$
$$v = \frac{E}{B} = \frac{V}{Bd}$$

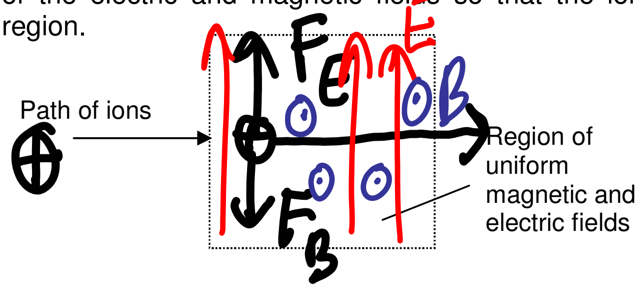
When we have many particles of different speeds being projected into this region, only particles of velocity $v = E/B$ will pass through undeflected.
For particles with speeds greater than this, the magnetic force will be larger than the electric force and deflect upwards.
For particles with speeds less than this, the magnetic force will be less than the electric force, and they deflect downwards.



Not all E and B fields that are perpendicular to each other will work as a velocity selector. It is important to note that the concept behind this application is that the particle experiences no resultant force when travelling in the crossed fields. Hence it is important to ensure that the direction of the electric force is opposite to the direction of the magnetic force set up by the two fields.

Example 10

Ions produced by an ion source are accelarated from rest through a potential difference and are then injected into a region of space where there are uniform electric and magnetic fields acting at right angles to the orginal motion of the ions. Indicate on your diagram the directions of the electric and magnetic fields so that the ions can pass through undeflected through the region.



16.5.2.3 The Mass Spectrometer

A mass spectrometer separates ions according to their mass to charge ratio. In the Bainbridge mass spectrometer, a beam of ions first passes through a velocity selector and then enters a second uniform magnetic field, which has the same direction as the magnetic field in the selector as shown in Figure 16.5.9.

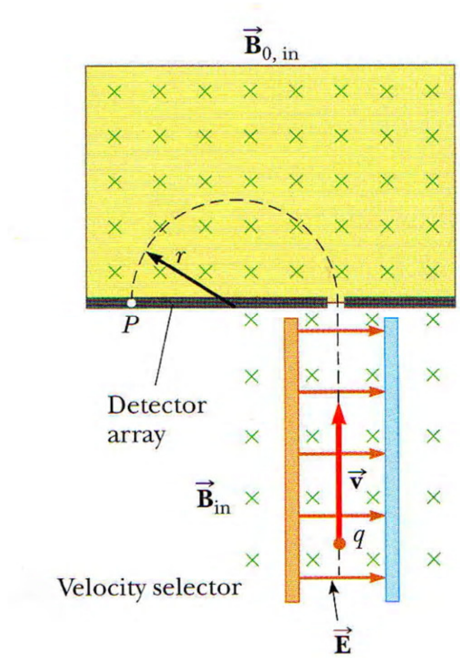


Figure 16.5.9 Mass spectrometer

Upon entering the second magnetic field, the ions move in a semicircle of radius r before striking a detector array at P. If the ions are positively charged, the beam deflects to the left as shown, and if the ions are negatively charged, they will deflect to the right.

16.5.2.4 The Cyclotron

A cyclotron is a device that can accelerate charged particles to very high speeds. The energetic particles produced are used to bombard atomic nuclei and thereby produce nuclear reactions of interests to researchers.

Both electric and magnetic forces play a key role in the cyclotron. The charges move inside two semicircular containers D_1 and D_2, referred to as dees. A high frequency alternating potential difference is applied across the dees and a uniform magnetic field is directed perpendicularly to them. A positive ion released at P near the center of the magnet in one dee moves in a semicircular path (as shown by the dotted line) and arrives back at the gap in a time interval of $T/2$ where T is the time needed to make one complete trip around the dees.

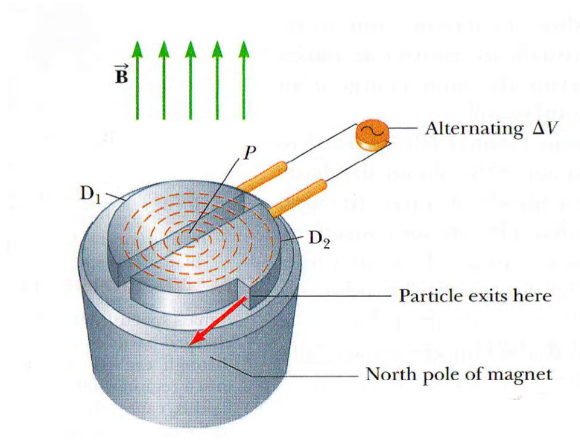


Figure 16.5.10

The frequency of the applied potential difference is adjusted so that the polarity of the dees is reversed at the same time interval during which the ion travels around one dee. The ion then accelerates across the gap from D_1 to D_2 and its kinetic energy increases by $q\Delta V$ where ΔV is the potential difference set up across the dees.

It now moves with a larger radius in D_2 due to the increase in speed. After *T*/2, it arrives at the gap again, coinciding with the reversing of the polarity of the potential difference set up across the dees. The ion thus accelerates again across the gap and the cycle repeats itself. Every time the ion passes the gap, it gains an energy of $q\Delta V$. By the time it exits the cyclotron, it would have garnered about 20 MeV.

16.6 Hall Effect

When a current carrying conductor is placed in a magnetic field, a potential difference is generated in a direction perpendicular to both the current and the magnetic field. This phenomenon, first observed by Edwin Hall (1855-1938) in 1879, is known as the Hall effect.

To explain the Hall effect, consider a slab of metal carrying a current. The flow of electrons is opposite to the conventional current. If the metal is placed in a magnetic field *B* at right angles to the face AGDC of the slab and directed out of the page, a force *Bev* then acts on each electron in the direction from CD to AG. Thus electrons are deflected downwards and collect along the side AG of the metal, which makes AG negatively charged and lower its potential with respect to CD.

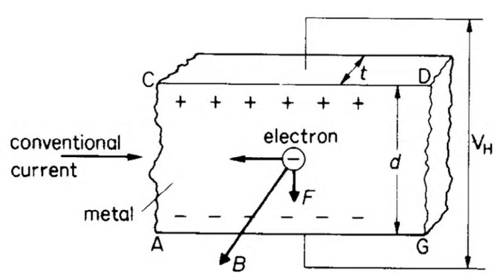


Figure 16.6.1

This accumulation of charge at the edges establishes an electric field in the conductor and increases until the electric force on the electrons remaining in the bulk of the conductor balances the magnetic force. When this equilibrium condition is reached, the electrons no longer deflect downwards. A sensitive voltmeter connected across the conductor can measure the potential difference set up, known as the Hall voltage.

Appendix 1 Charged particles moving in a non-uniform magnetic field

When charged particles move in a non-uniform magnetic field, the motion becomes complex. An example of such field is one where it is strong at the ends and weak in the middle as shown in the figure below. This configuration is known as the magnetic bottle. A charged particle starting at one end spirals along the field lines until it reaches the other end, where it reverses its path and spiral back. The charged particle is therefore trapped within it.

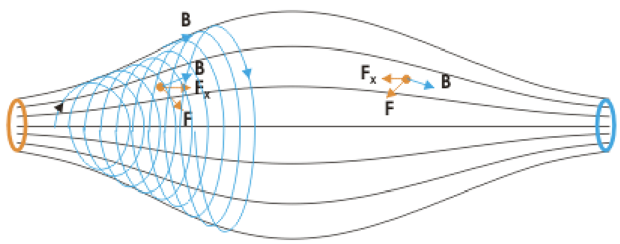


Fig 1 Magnetic Bottle

Another example is the Van Allen radiation belts consisting of charged particles (mostly electrons and protons) surrounding the Earth in doughnut-shaped regions (Figure 2).

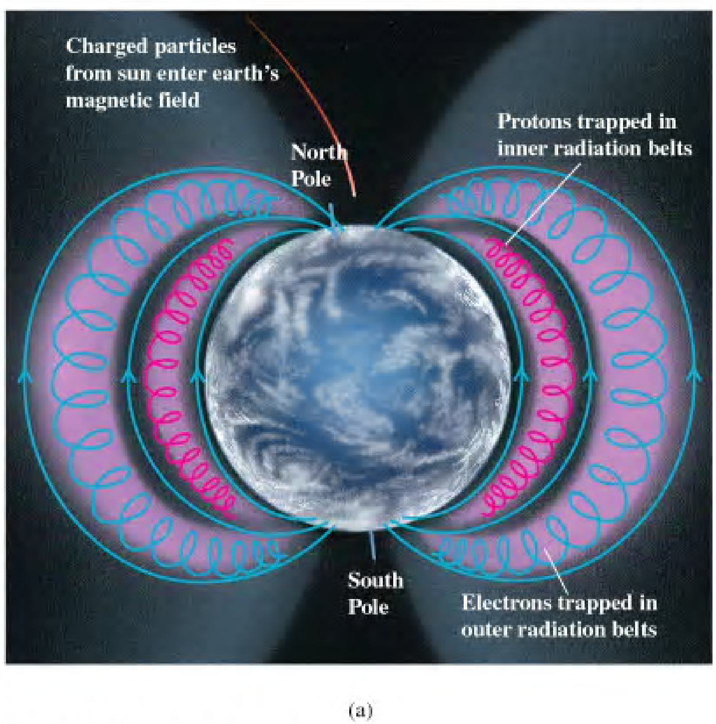


Figure 2 The Van Allen belts

Charged particles originate mainly from the sun (and other stars and heavenly bodies) and are commonly known as cosmic rays. Due to the Earth's non-uniform magnetic field, some of these particles are trapped and spiral around the field lines from pole to pole, making the Van Allen belts. When the particles are located near the poles, they sometimes collide with the atoms in the atmosphere , causing atoms to emit visible light. Such collisions are the origins of the beautiful Aurora Borealis (Northern Lights) and Auroras Australis.

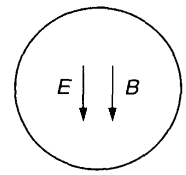
Figure 3 The Aurora Borealis

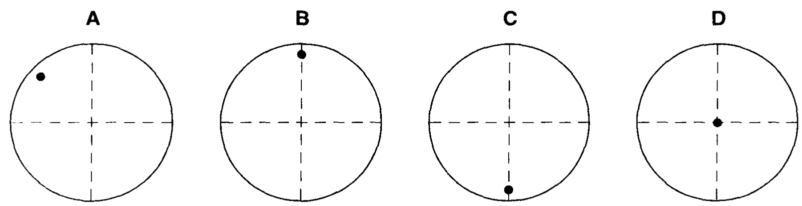
Tutorial 16C: Moving Charge in an Electric and Magnetic Field

Self Practice Questions:

1. J97/I/27: In a cathode ray oscilloscope tube, the electron beam passes through a region where there are electric and magnetic fields directed vertically downwards as shown.The deflections of the spot from the centre of the screen produced by both the electric and magnetic field acting separately are of equal magnitude. Which diagram shows a possible position of the spot on the screen when both fields are operating together? (HINT: the electrons travel out of the paper since the screen is shown on the paper)

front view of screen



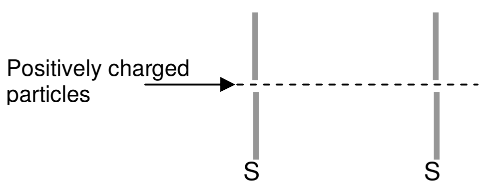


2. A small mass experiences a force when placed in a field of force. The field may be electric, magnetic or gravitational. State the type of field when the mass is

   a) uncharged and the force is in the direction of the field
   b) charged and the force is in the opposite direction to the field
   c) charged and the force is experienced only when it is moving

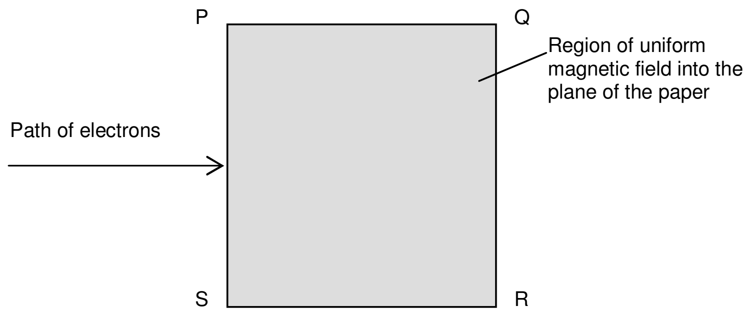
Discussion Questions:

3. J93/II/7: A narrow beam of identical positively charged particles pass through two slits S_1 and S_2 as shown.



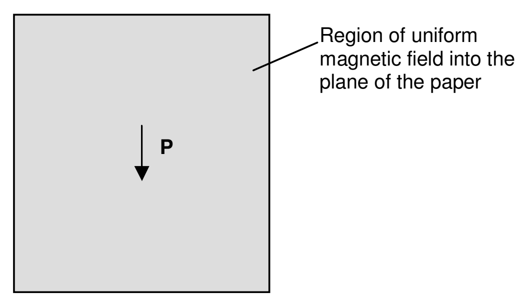
   A uniform magnetic field of flux density *B* is applied in the region between S_1 and S_2 in the direction out of the plane of the paper.
   a) A uniform electric field is applied in the space between the slits such that charged particles of only one speed *v* can pass through S_2. On the diagram, mark clearly with an arrow labelled *E* the direction of this field.
   b) Explain how this combination of magnetic and electric fields allows particles of only one speed to pass through S_2. Deduce an expression for *v* in terms of *B* and *E*.
   c) Sketch on the diagram, a possible path in the region of the electric and magnetic fields, of particles having a speed greater than *v*.

4. N01/II/8: The diagram shows a region PQRS of a uniform magnetic field directed downwards into the plane of the paper. Electrons, all having the same speed, enter the region of the magnetic field.



a) On the diagram, show the path of the electrons as they pass through the magnetic field, emerging from the side QR.
b) A uniform electric field is also applied in the region PQRS so that the electrons now pass undeflected through this region. On the diagram, mark with an arrow labelled *E*, the direction of the electric field.
c) The undeflected electrons in (b) each have a charge -*e*, mass *m* and speed *v*. State and explain the effect, if any, on particles entering the region PQRS of the same magnetic and electric fields as in (b) if the particles each have
   i) charge -*e*, mass *m* and speed *2v*
   ii) charge +*e*, mass *m* and speed *v*

5. N03/II/6: (b) An electron is travelling at right angles to a uniform magnetic field of flux density 1.5 mT, as shown. The field is directed into the plane of the paper. When the electron is at P, its velocity is 2.9×10^7 m s^{-1} in the direction shown. This is normal to the magnetic field.



   i. Sketch the path of the electron on the diagram, assuming that it does not leave the region of the magnetic field.

   ii. Calculate for this electron
      1. the force on it due to the magnetic field
      2. the radius of its path

   iii. A uniform electric field is now produced in the same direction and in the same region as the magnetic field. Suggest the shape of the resultant path of the electron. You may draw a sketch to illustrate the path, if you wish.

Solutions for 16C:

1. A

2 a). Gravitational Field   b) Electric Field   c) Magnetic Field

5. ii. 1. 6.96×10^{-15} N   2. 0.11 m